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THE PROBLEM OF GLIDER TAKEOFF USING A TOW WINCH

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ABSTRACT: Theoretical and experimental analysis of the mechanics of glider takeoff using a tow winch, with particular consideration of the loads applied to the glider. The glider's flight path at takeoff is examined during three different phases: (1) sliding or rolling over the ground till the moment of lift-off, (2) transition into climbing flight, and (3) climbing flight until the instant of release. The length of the first phase is determined in terms of the necessary air speed. The force exerted by the winch is studied in relation to ground friction and forces present in the towing cable. The lengths of the subsequent phases are similarly considered, and the effects of cable shape are studied. The equilibrium of forces acting on the glider is outlined in terms of the aerodynamic force, the gravitational force, and the towing force. Flight speeds and towing forces are experimentally determined for two different gliders and tow winches.

Glider takeoff using a tow winch is a fairly complex process. In /11[3] practice it is impossible to calculate many of the factors exerting an influence on the takeoff process, one such as individual control of the glider by the pilot, operation of the tow winch by the winch mechanic, the flying qualities of the glider, the characteristics of the tow winch, head wind, the elasticity of the towing cable, etc. Similarly, it is impossible to solve the problems of optimalization of the takeoff process by calculation. There are a few papers which deal with the process of takeoff by use of a tow winch from the theoretical standpoint. However, in order to create the possibility of analysis, certain parameters are not taken into account and certain variables during takeoff are assumed to be constant. Hence calculations are conducted on the assumption of a constant load factor or a constant flight speed. The results of such calculations are not satisfactory because the assumptions made do not correspond to actual conditions and are not confirmed by practice [1] and [3].

Useful results were obtained for the first time by Gedeon, who measured the parameters of takeoff of the "Meise" glider using the "Herkules" tow winch at the Budapest Polytechnical Institute [2]. Unlike the theoretical assumptions, these measurements in flight revealed that the load factor during normal takeoff using a tow winch is not constant but increases continuously

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3 Numbers in the margin indicate pagination in the foreign text.

as the takeoff process progresses. On the other hand, the force in the towing cable of the glider is approximately constant. Since these measurements are restricted to only one type of glider and one type of tow winch, the entire takeoff problem cannot be fully explained with them. In the German Democratic Republic there had for some time been a need for dealing more thoroughly with the problem of takeoff using a tow winch. When the Czechoslovak high-strength tow winches of the "Herkules" type were introduced, it became possible to exceed the permissible glider towing speed (especially in the case of the "Baby" glider) and it was feared that the design might be overloaded. Other difficulties arose with the old tow winches of the "Maybach" type, in the case of their use for two-person gliders. On the test bench these engines exhibited a power of 94 metric horsepower, which is recognized to be necessary in the case of two-person gliders, but sufficient altitude is often not attained at the air field under less favorable conditions, with a small head wind. Views have differed and misunderstandings have arisen concerning the load to which the glider design is subjected and the length of the breakaway cord connected to the towing cable.

At the beginning of 1962 an agreement was concluded between the Light Design Institute (IfL) in Dresden and the Civil Aeronautics Aviation Control Equipment Center (PfL/ZL) in Pirna on joint work to solve the problem of take-off using a tow winch. /12

As a result of analysis of the not overly extensive literature on this subject, first the equations were established which define the flight path process and the flight altitudes achieved, and an estimate was made of the tow winch power required.

These measurements could then be compared with the results of measurements in flight. Such measurements in flight were made by a work group in autumn of 1962 in Riese-Canitz.

The Mechanics of Takeoff Using a Tow Winch

First of all certain relations, known at least in part, which pertain to the mechanics of takeoff using a tow winch should be cited. Figure 1 illustrates the flight path during takeoff using a tow winch.

The flight path may be divided into three phases:

1) Sliding or rolling along the ground until breakaway at a speed of $v = 1.2v_{cl}$,

2) Transition to climbing flight,

3) Climbing flight to the instant of release.

During the first phase the glider must be accelerated from a state of rest to the speed of breakaway from the ground. The critical moment is starting off from a position of rest, when constant capability for acceleration is necessary. When the force of friction is present the lightening action of the aerodynamic lift is not exerted and every uneveness of the ground manifests itself immediately as a perturbing factor. A force in the towing cable of at least 50 to 100 kg is required to overcome the force of friction of the glider, depending on the type of glider and the condition of the airfield surface, it being assumed that the ground is even and that the glider is provided with wheels. (The value of the coefficient of friction $\mu = 0.08$ to 0.10 in the case of wheels; $\mu = 0.30$ for skids; $\mu = 0.50$ to 0.1 for a cable.) These minimum values are greatly exceeded in the event of sandy ground and skids.

In the case of a tow winch of the "Herkules" type, on the basis of the results of measurements one may anticipate the occurrence of a constant force in a towing cable of the order of $S \approx 250$ to 280 kg during the takeoff run. In the case of a tow winch of the "Maybach" type the force amounts to $S \approx 160$ to 200 kg.

Figure 2 shows the length of the takeoff run to the point of breakaway at $v = 1.2v_{z1}$ as a function of wind speed. The length of the takeoff run was calculated in this case by integrating the known condition of equilibrium of the forces during the takeoff run:

$$\left(\frac{G}{g}+\frac{G_s}{g}+\frac{G_G}{g}\right)\frac{dv}{dt}+(G-A)\mu+W+G_s\mu_s-S=0$$

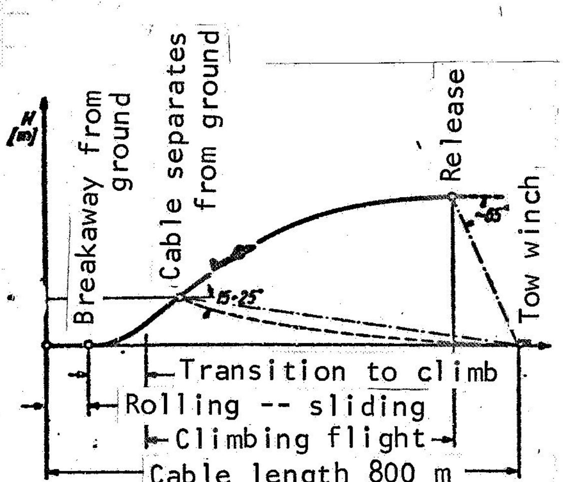

Figure 1. Flight Path During Takeoff Using a Tow Winch (Diagrammatic Representation).

Measured Values:	+ "Lehrmeister"; "Herkules" tow winch
	0 "Baby"; "Maybach" tow winch
	● "Baby"; "Herkules" tow winch
Calculated Values:	— $V_{br} = 1.2 \cdot V_{z1}$; $\mu = 0.08$; $\mu_{cable} = 0.5$

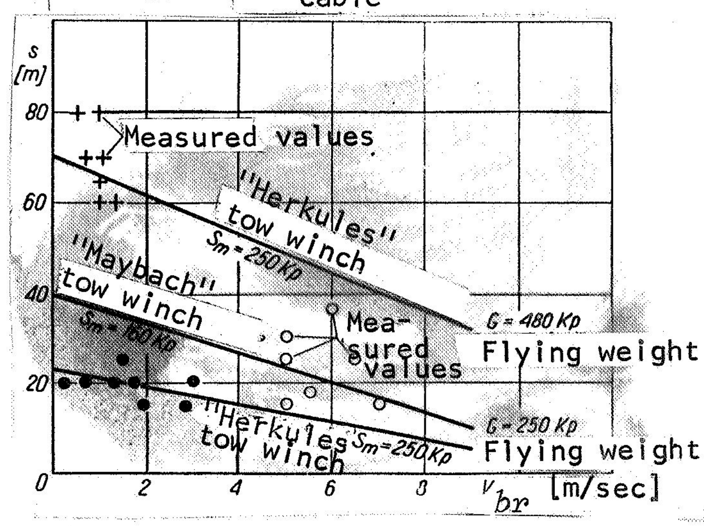

Figure 2. Rolling Path Along Ground to Point of Breakaway by Glider at V + 1.2V$_{z1}$ as a Function of Wind Speed.

The values obtained from measurements during flight are also given for the sake of comparison. The wide scattering of the point in the case of the "Maybach" tow winch is due largely to engagement of the clutch, this being the result of the skill of the mechanic operating the tow winch.

During the second phase the glider after breaking away from the ground is brought into the climbing flight position by corresponding manipulation of the elevator. The stretch length corresponding to this is:

$$s_2 = \frac{(1{,}2\, v_{s1})^2}{g} \; \frac{\sin \gamma}{n - \cos \gamma} \left(1 - \frac{V_w}{1{,}2\, v_{s1}}\right)$$

It amounts to 50 to 80 m depending on the force in the towing cable, the weight of the glider, and the head wind.

The third phase includes climbing flight proper to the moment of release of the glider. On the assumption of a weightless towing cable exhibiting no sag, the altitude may be calculated from the equation:

$$H = L_s \sin \varphi$$

According to Rade [3] the length of the towing cable L_s may be determined with the formula:

$$L_s = L_o\, exp \int_{\varphi_o}^{\varphi_1} \frac{v_s/v \; d\varphi}{\sqrt{1-(v_s/v)^2}}$$

With G/S assumed to be constant, the speed of the towing cable referred to the flight speed is obtained from the equation:

$$\frac{v_s}{v} = \frac{\cos \varphi}{\sqrt{(S/G)^2 + 2S/G \sin \varphi + 1}} + \frac{c_W}{c_A} \sqrt{1 - \frac{\cos^2 \varphi}{(S/G)^2 + 2S/G \sin \varphi + 1}} \approx (v_s/v)_0 (1 - k\varphi)$$

It follows from the measurements in flight themselves and from reference [2] that, owing to failure to allow for the sag of the towing cable, the cable speed actually is 1.22 to 1.27 times greater than that yielded by the foregoing equation. /13

Hence, the cable speed under windless conditions will be

$$v_s \cong 1{,}25\; v\; (v_s/v)_o\; (1 - k\, \varphi)$$

This equation is obviously valid when the cable is completely suspended above the ground, this occurring at a cable angle $i_1 = 15° \text{ to } 25°$, depending on the force in the cable and its weight. When this angle is reached, the altitude usually amounts to approximately 80 m with a total cable length of 800 to 1000 m; distance S_2 and S_3, including the transitional arc, ranges from 150 m (for the "Baby" glider) to 210 m (for the "Lehrmeister" glider) under windless conditions:

$$L_{s_0 A} = L_{s_0 1} e^{\alpha}$$

with:

$$\alpha = -\frac{1}{1{,}25k\left(vs/v\right)^2}\left[\sqrt{1 - 1{,}25^2\left(v_s/v\right)_0^2 (1 - k\varphi_1)} + - \sqrt{1 - 1{,}25^2\left(v_s/v\right)_0^2 (1 - k\varphi_1)^2}\right]$$

and:

$$L_{s_0 1} = L_0 - s_1 - s_2 - s_3 \quad \text{(cf. Fig. 2)}$$

Release occurs at a towing cable angle of 60° to 65°. The flying altitude reached may be calculated in approximation from the equation:

$$H_A = (L_s - 5) \sin\left[(60° \text{ do } 65°) - 5°\right]$$

Reduction of the cable length by 5 m allows for shortening of the chord in relation to the actual cable length. Due to cable sag, the glider-tow winch-ground angle is reduced by about five degrees in comparison with the cable angles during release.

Figure 3 shows the flight path for the condition S/G of 0.65 and 1.25 deriving from the equation cited, for calm and with cable sag taken into account. The calculated flight path agreed closely with the measured flight path. It should be pointed out that during the flight test an influence was exerted by the wind and the force in the towing cable was not completely constant.

The power required of the tow winch for climbing flight consists of four components:

Glider weight X climbing speed,
Aerodynamic resistance of glider X flight speed,
Cable weight X (average) cable climbing speed,
Aerodynamic resistance of cable X (average) cable speed relative to the air:

$$N = G\left(v \sin\gamma + v \frac{c_W}{c_A}\right) + G_s \frac{v}{2} \sin\gamma + \frac{3}{4} W$$

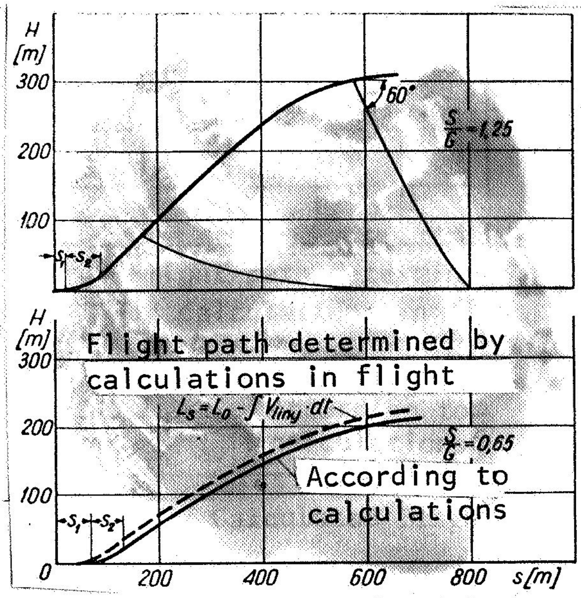

Figure 3. Calculated Flight Path.

The force referred to the weight of the glider may be calculated from the equation:

$$\frac{S_w}{G} = \frac{v}{v_s}\left(\sin\gamma + \frac{c_W}{c_A} + \frac{G_S}{2G}\sin\gamma + \frac{3}{4}\,\frac{W_S}{G}\right)$$

and the flight path angle from:

$$\sin\gamma = \frac{1}{G + \frac{G_s}{2}}\left(S_W\,\frac{v_S}{v} - \frac{c_W}{c_A}\,G - \frac{3}{4}\,W_S\right)$$

The altitude reached is thus proportional to the available force in the cable relative to the torque of the towing winch and inversely proportional to the weight of the glider.

Since climbing flight constitutes the predominant portion of the entire takeoff, the available torque is decisive for reaching the flight altitude.

The cable speed decreases constantly during climb. Hence it is especially important that sufficient pulling force be available even at low speeds of the towing cable, i.e., that sufficient torque be maintained at low engine speed.

Loads Applied to Glider During Takeoff Using a Towing Winch

All the forces acting on a glider must be in equilibrium. In steady towed flight the resultant aerodynamic force is balanced by the resultant of the weight and the force in the towing cable. The curvature of the flight path, and consequently the certrifugal force, are small and may be ignored. A greater centrifugal force occurs only during transition to climbing flight. The resultant aerodynamic force may by known methods be decomposed into the /14 aerodynamic lift and resistance, and since the aerodynamic lift by definition is perpendicular to the direction of flight, the direction of flight is also obtained regardless of flight speed. Hence the pilot cannot influence the direction of flight or the angle of climb by means of the elevator, since these parameters are determined by the value and direction of force in the towing cable.

While during free horizontal flight the aerodynamic lift is directed opposite the total weight of the glider and balances it, in curvilinear flight, in a loop, during pull-up or during a turn, a centrifugal force also occurs, and the load on the glider is a multiple of the weight of the glider. The pilot may estimate the load by the force with which he is pressed into the seat or by the force pressing him against the belt. Hence the pilot has a sort of built-in accelerometer and by it estimates the load on the glider. He manipulates the controls so that neither he himself nor the glider will be subjected to overly great loads.

The actual bending load on the wing is caused by the aerodynamic lift, the weight of the wing exerting a load removal effect. In the case cited of the "Baby" glider the load removed from the wings and caused by the weight of the glider amounts of 36% of the total load (Cf. Figure 5, bottom).

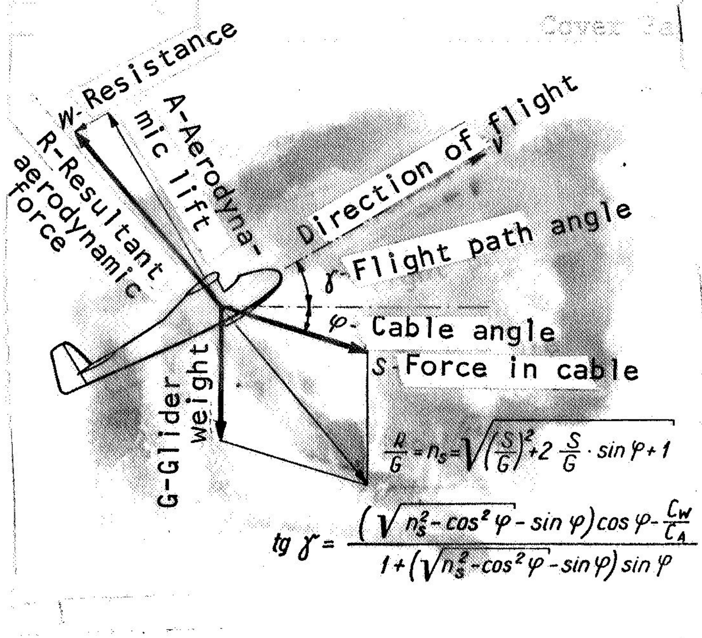

Figure 4. Forces Acting on a Glider in Steady Towed Flight

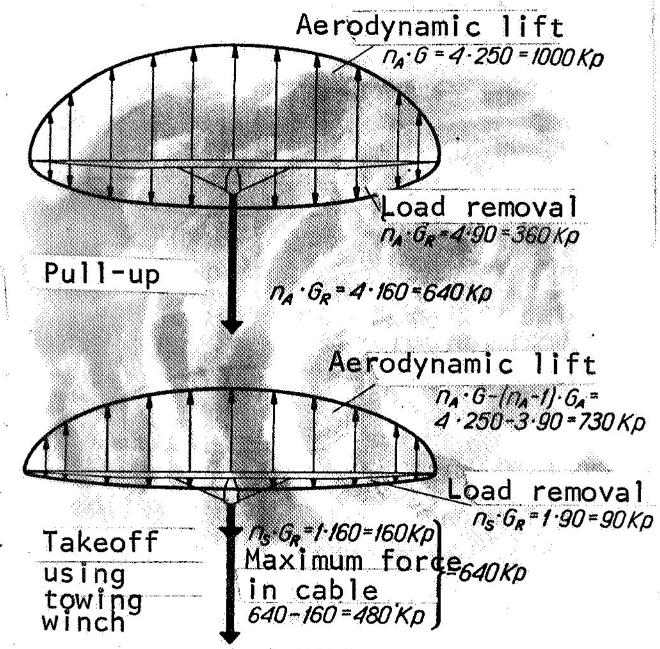

Figure 5. Permissible Load for Airfoils of "Baby" Glider.

The situation is different during towed flight. Because of the slight curvature of the flight path, the centrifugal force is small, the load factor is near unity, and the pilot cannot by his "accelerometer" estimate the load to which the glider will be subjected. Load removal from the wings is minimal (Cf. Figure 5, bottom). The permissible force in the towing cable relative to the strength of the glider may be calculated according to the existing bending strength of the wing and by allowing for the minimal load removal due to the action of the dead weight of the wing. Such values for different gliders are given in Figure 6.

The maximum permissible flight speed during takeoff using a towing winch is generally specified so that exceeding the permissible wing load will not be possible during flight with the maximum possible lift coefficient up to this speed.

The range available between the speed permissible for strength considerations and that determined by the maximum lift coefficient is fairly narrow. /15
In towed flight the minimum flying speed is greater than in free flight, since the force in the cable must also be "borne".

Figure 7 illustrates the situation during towing of the "Baby" glider by the "Herkules" towing winch.

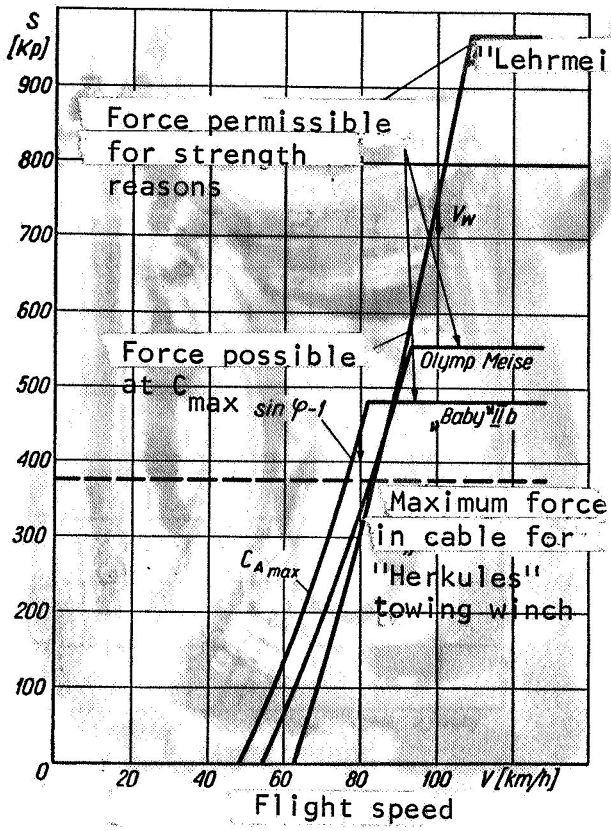

Figure 6. Possible Forces in Towing Cable for Individual Glider Types.

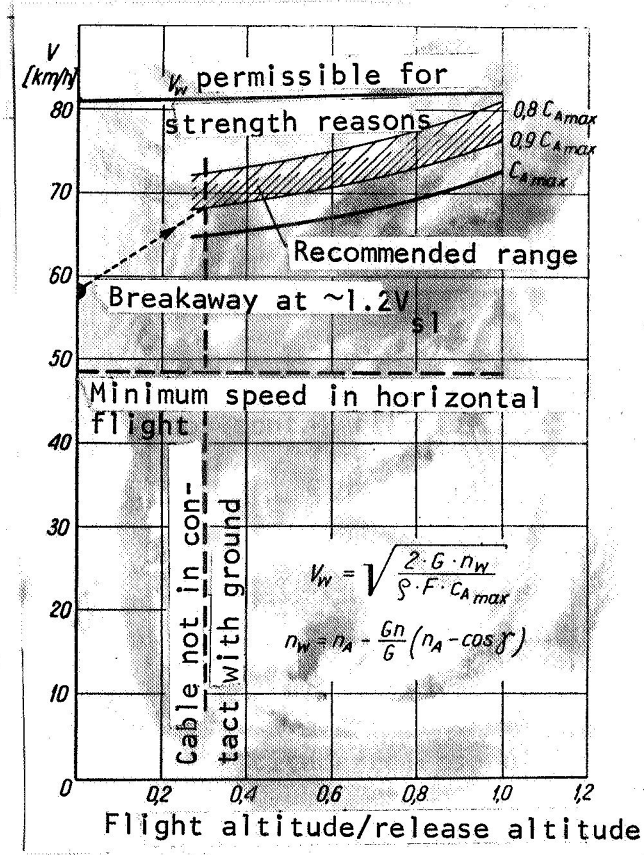

Figure 7. Range of Flight Speed During Takeoff Using Towing Winch ("Baby" Glider, "Herkules" Towing Winch).

Flight Tests

The measurements were conducted with two of the towing winches the most commonly used in the GDR. The "Maybach" towing winch is provided with a gasoline engine of a power of 94 metric horsepower, a four-speed gearbox, and a conventional clutch worked by a pedal. The "Herkules" towing winch, on the other hand, is provided with a "Tatra" Diesel engine of a power of 134 metric horsepower. In place of a drive engaged mechanically, it has a hydraulic clutch permitting the transmission of torque even at low engine speeds.

In order to achieve the widest possible measurement range, tests were conducted on the one hand with the lightest glider, the "Baby", of a flying weight of 250 kg and on the other with the heaviest, the "Lehrmeister", of a weight of 500 kg. Despite the short period during which measuring instruments were available it was possible to make 29 test flights.

The following parameters were measured by means of automatic recording devices in order to obtain useful results from the flight test:

Flying speed and altitude, on the glider,

The force in the towing cable and the speed of this cable on the towing winch, and in the case of the "Herkules" towing winch also the engine speed.

The principal element of the measuring equipment on the towing winch was an instrument for measuring the force and speed of the towing cable (Figure 8).

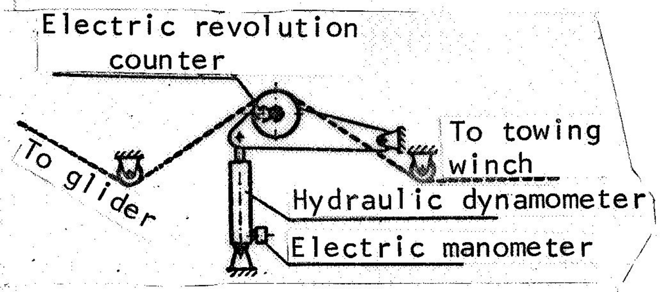

Figure 8. Equipment for Measuring Force in Cable and its Speed (Diagrammatic Representation).

In this arrangement the cable passes through two guide rolls and in the center through a measuring roll secured in an eccentric position. The pressure in the hydraulic servomotor is a gauge of the force occurring in the cable. Cable speed is measured by means of the voltage of an electric current from a generator coupled to the guide roll. The measured values of the force in the cable, cable speed, and the engine speed in the case of the "Herkules" towing winch are transmitted electrically to a three-channel automatic recorder which enters the parameters on a paper band. In the case of the "Maybach" towing winch installation of the tachometer would require more extensive modifications. The measuring equipment was supplied by a 220-volt generating set. The entire measuring equipment was calibrated and performed very well during operation.

Figure 10 illustrates the measuring system. The instrument for measurement of the force and speed of the towing cable was secured on the chassis of the old "Maybach" winch and set in front of the "Herkules" winch used for measurement.

The recording of the takeoff of the "Baby" glider using the "Herkules" towing winch is shown in Figure 11. The recordings are to be read from right to left. The parameter values entered in the diagram were obtained on the basis of graduation of the equipment. Before the takeoff itself, i.e., before the glider starts movement, increase in the force in the cable caused by cable /16
tension is to be observed. The cable speed is very low and the engine idles. Then the force in the cable, the cable speed, and the engine speed increase considerably - the glider undergoes sharp acceleration on the ground, and after reaching a certain minimum speed separates from the ground and makes the transition to climbing flight. During passage through the transitional arc (before climb) the glider is further accelerated; this is to be seen from the increasing speed of the towing cable. The ensuing decrease in cable speed and the decrease in engine speed are the results of steering by the pilot. Although the winch mechanic presses the throttle lever to the limiting

position, the glider pilot causes throttling of the winch engine in order to achieve the proper flying speed and cable speed.

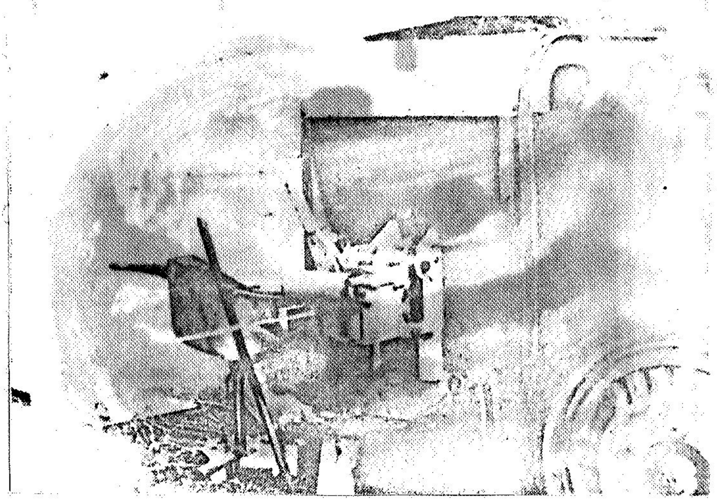

Figure 9. Arrangement of Measuring Equipment in Old Towing Winch.

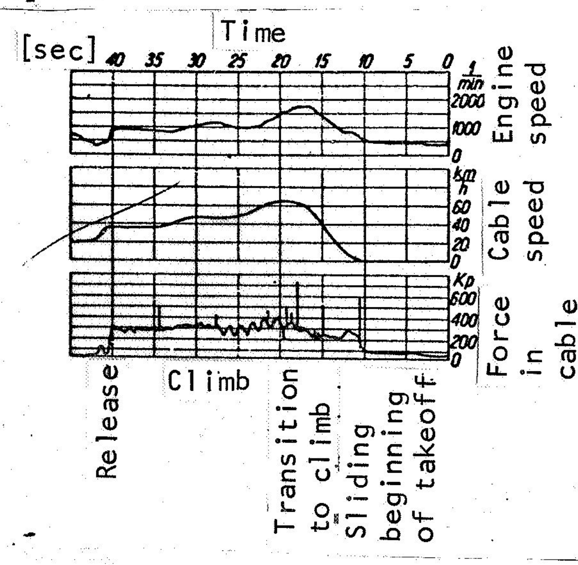

Figure 10. Recording of Takeoff of "Baby" Glider Using "Herkules" Towing Winch.

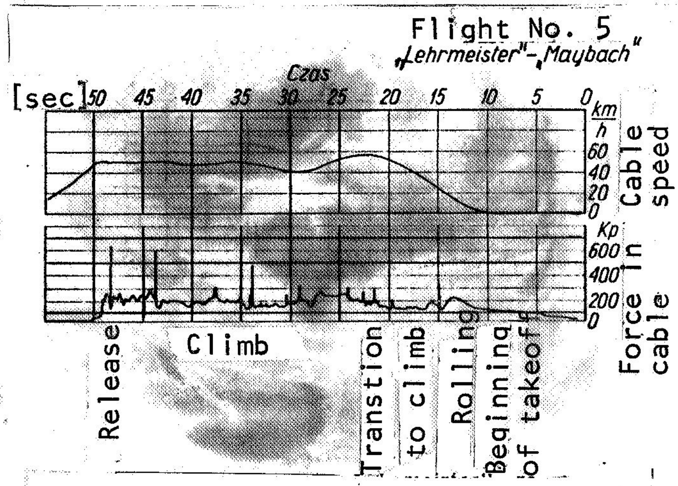

Figure 11. Recording of Takeoff of "Lehrmeister" Glider Using the "Maybach" Towing Winch.

The periodic oscillations of the force in the cable to be seen in the diagram and ranging up to 50 kg are the natural oscillation of a mass-spring system, the spring being represented by the elastic sagging cable under tension, and the mass of the oscillating system being represented by the glider. Theoretical calculation of this frequency is difficult because sufficient data are not available on a constant spring and elastic damping in the presence of aerodynamic forces. These oscillations are closely related to the fluctuations of the angle of attack of the glider, as has been demonstrated by calculations. The measured frequencies range from 0.6 to 1.0 Hz.

These load fluctuations are also so large and frequent that they must be taken into account in investigation of the fatigue strength of gliders. Measurements show that during every takeoff approximately 25 load fluctuations occur. A glider which may be used for twelve years (if it is a training glider) and during this period perform around 7,000 takeoffs thus undergoes 25·7000 = 175,000 load variations during the entire period of use. This, in addition to other effects, must be taken into account in determining the certain (safe) service life of a glider.

A recording of the process of takeoff of the "Lehrmeister" glider using the "Maybach" towing winch is given in Figure 12. The individual phases of takeoff from beginning to release are also to be clearly seen in this illustration. The pronounced surges in the force in the cable are caused by impacts during uneven unwinding of the cable from the drum. They last only 1/22 to 1/40 of a second and reach values of 400 to 800 kg. Because of the extensive damping by the cable these forces are not transmitted to the glider.

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